Speed and Surge Control for an Unmanned Aircraft Vehicle with Turbojet Engine

Min-Seok Jie and Beyong-In Jung

Abstract This paper proposed fuzzy PID controller which prevents compressor surge and reduces the acceleration time of the fuel flow control system for turbo-jet engine. The fuzzy PID controller is to stabilize the unmanned aircraft vehicle upon occurring unexpected engine surge. This controller is designed by applying fuzzy PID control algorithm, inferred by applying Mamdani's inference method and defuzzified by using the center of gravity method. Fuzzy inference results are used as the fuel flow control inputs to prevent compressor surge and flame-out for turbo-jet engine. The controller is designed to converge to the desired speed quickly and safely. The performance of the proposed controller is verified by performing computer simulations with MATLAB.

Keywords Turbojet engine · Fuzzy PID control · UAV · Fuel flow control · Surge control

1 Introduction

Turbo-jet engine used for commercial aircraft and unmanned aircraft requires proper control to ensure operational reliability within predictable operating range [1]. The fuel flow and the exhaust nozzle of area is the most important among the control measures of jet engine used in aircraft. Besides, control methods are used in air scoop, air bleed valve, turbo charger, lubrication system and control system. In general, take-off and landing distances should be short. Especially military aircraft

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requires high mobility. To satisfy the above requirements, turbo-jet engine acceleration time has to be short. But due to sharp increase in fuel flow could be occurred the state such as surge or over-temperature rise.

Instabilities that arise in the unsteady fluid and structural dynamics are among the main challenges in the design and operation of jet engines. These instability phenomena are compression system rotating stall and surge. The pressure of the air flow increases and the air flow into engine decreases. Therefore, surge causes a stall. Surge is an unstable operation mode of the compressor and the stability boundary in the compressor map is called the surge line.

Surge is characterized by oscillations in pressure rise and mass flow. These oscillations can cause severe damage to the machine' due to vibrations and high thermal loading resulting from lowered efficiency. Surge has been avoided using surge avoidance schemes.

Typically, a surge control line is drawn at a distance from the surge line, and the surge avoidance scheme ensures that the operating point does not cross this line. This method restricts the operating range of the machine, and efficiency is limited. It is important to control the fuel flow effectively that is the nub of jet engine controller design.

Likewise each system should be installed with electronic system in order to control the aircraft engine automatically under optimum conditions. Small engine as unmanned aerial vehicle limit the dimension of exhaust nozzle to simplify system. So the engine control system suited to SISO (Single Input Single Output) system should be designed to achieve desired engine performance by controlling fuel flow effectively.

PID control method should be applied to control the turbo-jet engine. The characteristics of jet engine system were established and tracking control for baseline based PI control method has been generalized. The application of different control approaches has been studied to improve efficiency of the turbo-jet engine such as ECU algorithm of turbo-jet engine for calculating the fuel flow by applying fuzzy logic [2] and the fuel flow controller using neural networks [3, 4].

This paper designs approach applying fuzzy inference method to small turbo-jet engine for unmanned aircraft in which fuel flow is used as a single input.

The efficiency of the fuzzy rule will depend on variables set such as fuzzification/defuzzification, fuzzy inference. We establish the fuzzy control rule from the results of existing PI controller and will design the fuzzy PID controller. The proposed control method is proved by simulation using liner model engine. Also PID controller are compared with the controller.

2 Engine Control System Design

2.1 Turbojet Engine System

Turbo-jet engine for aircraft is the target model. The purpose of controller design for the input fuel flow control is to achieve a high thrust performance.

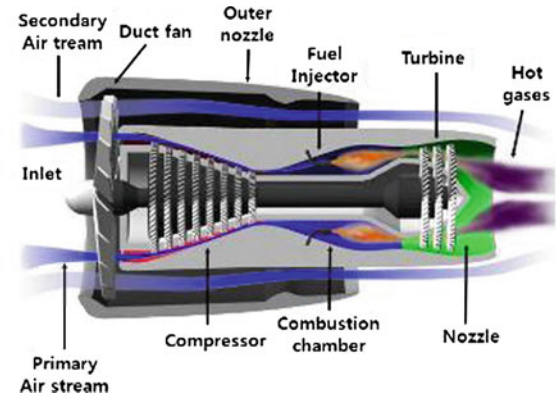

Fig. 1 Schematic of a turbojet engine

Simplified turbo-jet engine consists of the four main stages (Compressor, Combustor, Turbine, Nozzle) as shown in Fig. 1. The air is compressed by compressors. The compressed air then enters a combustion chamber where, in combination with fuel, it undergoes combustion in almost static pressure. High pressure gas is transferred in the turbine and rotated the turbine. And then the gas quickly erupts through the nozzle.

Since the engine thrust is in proportion to the rotor speed of compressor, the engine thrust can be estimated by measuring the rotor speed of compressor and the estimated thrust value can be applied to engine control system.

The engine acceleration and decrease controller is designed to control fuel flow so that the desired thrust can be controlled under the command of speed which is transferred into the rotor speed of compressor.

Acceleration control is achieved by setting a surge margin line in which sufficient surge margin is secured, and having engine control line to be positioned near the surge control line. In this case, if the reference command is set up as a compressor rotating speed, then in the initial stage the engine may run over the surge margin by sudden acceleration, however through the surge control, the fuel flow is controlled.

2.2 Fuzzy Controller Design

After Mamdani and Assilian make fuzzy controller which is based on fuzzy logic in 1974, fuzzy controller was realized easily and had good performance by applying to the steam engine control. The fuzzy controller was applied to the object which wants to control accumulated experience and knowledge of human. The control rule was designed mostly by professional's experience and knowledge. Particularly, the fuzzy controller has good performance in the system which has a lot of the control variables of process even if it is non-linear model and the linearization model [5].

PID controller which was well known has high performance at variety of environments and is used widely because it is control method which is a familiar to engineers. However, classical PID controller doesn't have good performance in the non-linear system.

Fuzzy controller has robustness for non-linear system because it can express verbalism. The fuzzy controller has been studied as PI type and PD type. The PI type is used universally because it can fix error of normal state to '0'. But, although the fuzzy PI type performs well in good condition in steady-state, it has limits that it can't improve performance in transient state and the PD type can't reduce steady-state error.

Fuzzy PID controller was suggested by the SIIM (Simplified Indirect Inference Method). Since Z.Y. Zhao and the rest suggested the PID gain regulator based of the fuzzy logic [6], also the PID controller study has progressed rapidly. Malki and the rest suggested the non-linear system fuzzy PID controller which was divided into 20ea of control input by applying the original 2ea of fuzzy input variable and 4ea of fuzzy rules, non-linear defuzzification which is based on the linear model of the digital PID controller.

Malki and the rest's fuzzy PID controller which is based on the linear digital PID structure is designed so that control performance of the linear structure should be the non-linear and time variant parameter gain. Therefore, it can establish the good performance in the linear plant and non-linear plant [7]. However, because the control input is divided to 20ea of domain by combination of fuzzy input and fuzzy input variables increase, it would be hard to apply, So controller of the fuzzy PI + D type or the fuzzy PD + I type is realized.

Figure 2 shows the structure of fuel flow control system which is setting reference speed in the light of surge control and is tracking for reference command [8].

We design the controller using fuzzy inference and define error between the compressor reference speed and actual speed.

$$e_N = N_R - N \tag{1}$$

Where, NR is compressor reference speed for control as the desired thrust and N is actual speed.

$$\begin{aligned} U_P(t) = K_P(e_N, e_P)e_N + K_I(e_N, e_P)\int_0^t e_N(\tau)d\tau \\ + K_D(e_N, e_P)\frac{de_N}{dt} \end{aligned} \tag{2}$$

Where, e_p is an error of compression ratio at inlet compressor. The control gain K_P, K_I and K_D are chosen as fuzzy inference method using e_N, e_P. Input variables of fuzzy inference models are defined e_N, e_P, the output variables are defined PID control gain weight value Q.

Table 1 shows all fuzzy rule and fuzzy rule is written in the same way as above.

The Table 1 defines the fuzzy rule of the input fuzzy variables and output fuzzy variables, and divides language value of input variable into 5 steps (NB, NS, ZE,

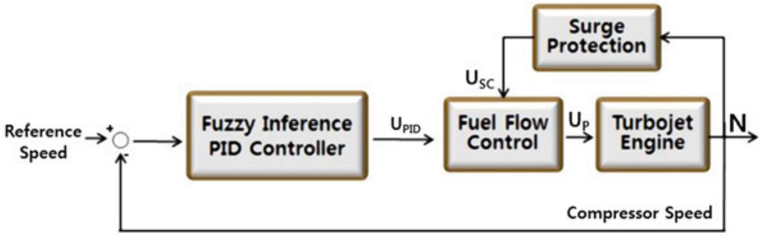

Fig. 2 Structure of the engine control system

Table 1 Fuzzy rule

e_N / e_P	NB	NS	ZE	PS	PB
NB	VB	VB	VB	VB	VB
NS	VB	M	S	M	VB
ZE	B	S	VS	S	B
PS	VB	M	S	M	VB
PB	VB	VB	VB	VB	VB

PS, PB) and the output fuzzy variables into 5 steps (VS, S, M, VB, B) and the membership function is defined as Fig. 3.

Response of the input fuzzy variables in closed-loop system is estimated based on expert knowledge, and fuzzy control rule was added in order to achieve control objectives.

Weight value Q is obtained through defuzzification using the center of gravity method.

If the language values of fuzzy input variables are $e_N = x_1^0$, $e_P = x_2^0$ and the goodness of fit (W_i) of the ith rule (R_i) is calculated as follows.

$$W_i = A_{i1}(x_1^0) \times A_{i2}(x_2^0), \quad \mathrm{i} = 1, 2\ldots\mathrm{n} \tag{3}$$

The result of inference of fuzzy rule (C_i') is generated by using Mamdani inference method,

$$\mu C_i'(Q) = W_i \times \mu C_i'(Q) \tag{4}$$

The result of inference of defuzzification using the center of gravity method ($Q = COG(C_i')$) is calculated as follows.

$$Q = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \tag{5}$$

We define the PID control gain inference result Q as follows.

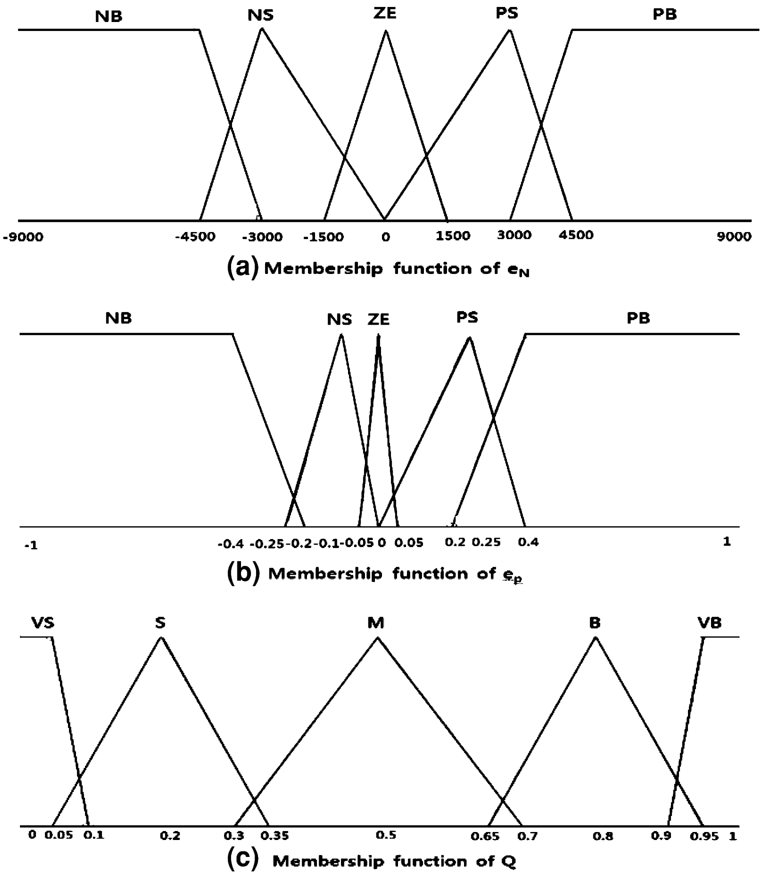

Fig. 3 Membership function of input and output variables

$$K_P = Q \times k_1, K_I = Q \times k_2, K_D = Q \times k_3 \quad (k_1, k_2, k_3 : constant) \tag{6}$$

Control gains decide the fuel flow for the control of engine speed.

3 Simulation

The performance of proposed fuzzy inference engine control method presented in this paper is shown by simulation using MATLAB. We use a linear model expressed with state space equation.

$$\dot{x}_P(t) = A_P x_P(t) + B_P u_P(t) \tag{7}$$

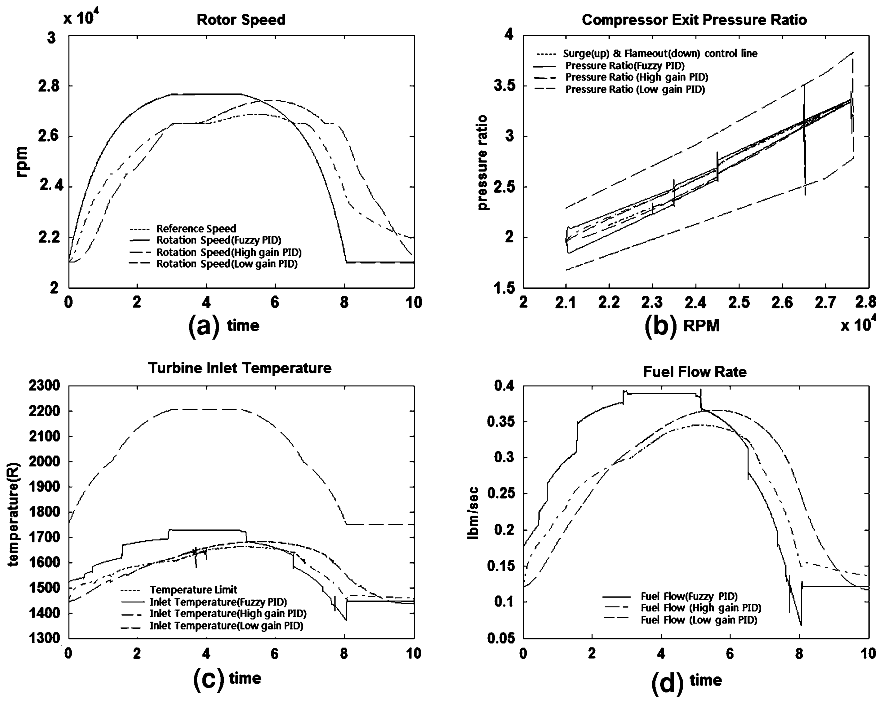

Fig. 4 Simulation results. **a** compressor rotation speed, **b** compressor outlet pressure ratio, **c** turbine inlet temperature, **d** fuel flow rate

Where, $x_P = \begin{bmatrix} x_{P1} & x_{P2} & x_{P3} & u_P \end{bmatrix}^T$: state vectors

x_{P1}: compressor rotation speed

x_{P2}: turbine inlet temperature

x_{P3}: compressor outlet pressure

u_P: fuel flow

As shown in Fig. 4, in the condition that the engine rotates at 21000 rpm, the engine is accelerated to 7000 rpm for 3 s, and then maintained at 28000 rpm for 3 s, and then decreased to 21000 rpm until 9 s.

Figure 4 shows engine speed according to reference speed, compressor pressure ratio, turbine inlet temperature, and fuel flow rate. Fuzzy PID controller does not exceed the limits of a surge control line and we can observe that the engine follows the reference speed command. On the other hand, PID controller shows obvious error between reference command and current state because it could not be tracked to reference value.

The control gains of the proposed fuzzy inference PID controller are chosen as $K_P = Q \times 0.0000027$, $K_I = Q \times 0.00003$, $K_D = Q \times 0.000002$. The weigh value Q is decided depending on the control state by fuzzy inference.

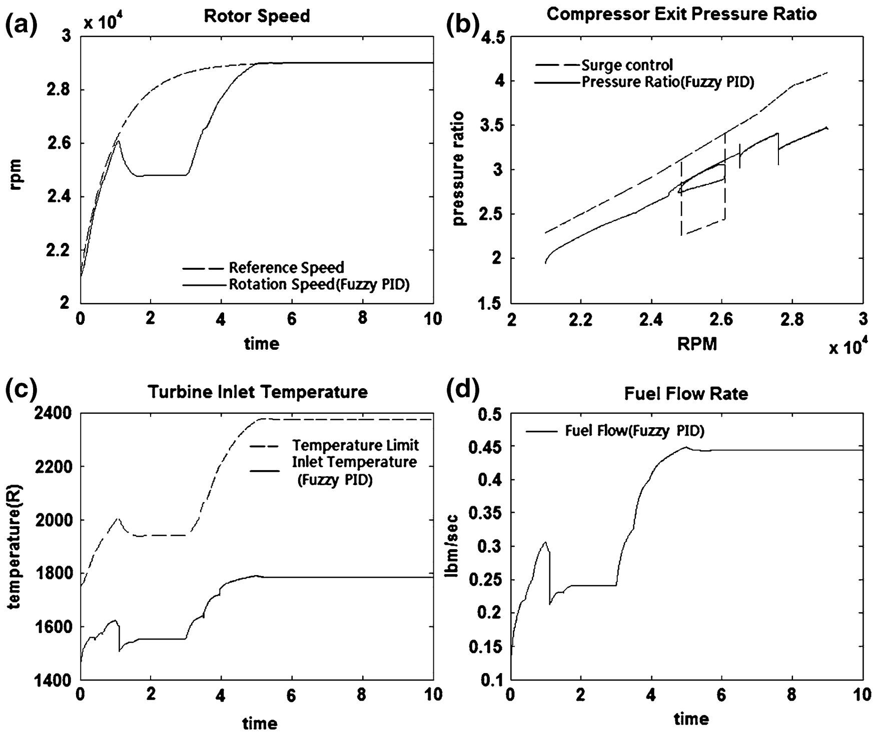

Fig. 5 Simulation results. **a** compressor rotation speed, **b** compressor outlet pressure ratio, **c** turbine inlet temperature, **d** fuel flow rate

The transient response of the feedback control system was improved using the cascade compensation. It has high response time and effective decreasing to steady-state error. The result of engine thrust is shown high efficiency in close proximity to surge control line.

Figure 5 shows results of the ability to protect the engine. The controller reduces compulsorily the fuel flow by 25% for 2 s when the compressor pressure ratio over the limits of the surge control line. This method makes it possible to engine operate under the surge control line with optimum surge protection feature which enable to eliminate unnecessary fuel flow drop and increase operation efficiency.

4 Conclusions

In this paper, we propose a turbo-jet engine controller of unmanned aircraft based on Fuzzy Logic and PID algorithm. Engine speed value is used as reference input and fuzzy inference rule is applied to PID control. By simulations, the proposed

controller is compared with the existing fuzzy controller. The proposed method effectively controls the fuel flow input of the control system and it has good tracking performance for the reference acceleration and deceleration commands. To prevent any surge or a flame out event during the engine acceleration or deceleration, the fuzzy controller effectively controls the fuel flow input of the control system.

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